Army Research Laboratory

Quantitative Gap Measurement in Ceramic Armor Arrays

by Seth Ghiorse, Ashiq A. Quabili, Renée Schoch,
William E. Fallon, and R.J. Sciortino

ARL-TR-5303 September 2010

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069

ARL-TR-5303 **September 2010**

Quantitative Gap Measurement in Ceramic Armor Arrays

Seth Ghiorse
Weapons and Materials Research Directorate, ARL

Ashiq A. Quabili
SURVICE Engineering Co.

Renée Schoch
Dynamic Science, Inc.

William E. Fallon and R.J. Sciortino
BAE Systems U.S. Combat Systems-Pennsylvania

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
September 2010	Final	1 October 2009−31 May 2010

4. TITLE AND SUBTITLE
Quantitative Gap Measurement in Ceramic Armor Arrays

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Seth Ghiorse, Ashiq A. Quabili*, Renée Schoch**, William E. Fallon***, and R.J. Sciortino***

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: RDRL-WMM-A
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-5303

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
*SURVICE Engineering Co., **Dynamic Science, Inc., ***BAE Systems U.S. Combat Systems-Pennsylvania

14. ABSTRACT
In order to reduce weight while maintaining ballistic performance, modern armored vehicles often use ceramic-based armor solutions. Ceramic solutions are typically made of a close-fitting periodic array of ceramic tiles, maintaining a specific gap dimension between the tiles. The gap separation distance is critical to the ballistic performance of the system and it is important to have a reliable means of quantitative inspection. This report presents results of a study of a non-destructive quantitative X-ray gap width measurement method commonly used to measure and inspect array gaps. It was found that this X-ray method gives a good portrayal of array quality and gap widths, but that gap measurement accuracy likely can be improved. The X-ray method was found to skew gap width measurements higher, between 2 and 20%, and was dependent on image blur. An X-ray system designed specifically for gap measurement will significantly improve measurement accuracy. Obtaining such a system is recommended, with digital X-ray radiography being the preferred path forward.

15. SUBJECT TERMS
ceramic array, quantitative gap measurement, X-ray, non-destructive evaluation, armor

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Seth Ghiorse
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
Unclassified	Unclassified	Unclassified	UU	40	(410) 306-0761

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

List of Tables

Acknowledgements

The authors thank Tom Deal and his team at the Aberdeen Test Center Industrial Radiography Facility, for performing all the X-rays and for their expertise and insights into X-ray testing.

The ceramic array test panels were provided by BAE Systems U.S. Combat Systems – Pennsylvania as part of a collaborative research program funded by the U.S. Army Manufacturing Technology (ManTech) Program, and sponsored by the U.S. Army Research Laboratory (ARL) under Cooperative Agreement Number W911NF-05-2-0002.

INTENTIONALLY LEFT BLANK.

1. Introduction

Weight reduction is highly desired across U.S. Army platforms and equipment. Armor is no exception to this, and ceramic-based armor is one common means of lowering armor weight while maintaining protection level. Ceramic-based armor is commonly made up of a periodic array of many tiles that cover the protected area. The gap width between the tiles is critical to ballistic performance. Accurate manufacturing control of the gaps, as well as reliable post-manufacturing gap inspection to assure the final product is within performance limits, is also necessary. This study addresses quantitative gap width measurement using post-manufacture X-ray. X-ray is the only practical non-destructive test method available to make quantitative width measurements of the gaps, as the tile array layer is located in the armor interior where direct visual inspection and measurement of the final product is not possible.

In order to assess the quantitative X-ray measurement system used at the U.S. Army Research Laboratory (ARL), two experimental tile arrays were fabricated at BAE Systems U.S. Combat Systems-Pennsylvania, York, PA (BAE). These arrays were made with one side open and uncovered so that baseline direct visual gap measurements could be made. The direct measurements from these arrays gave the accurate data needed to evaluate the efficacy of the X-ray data.

Direct tile gap measurements were made on the processed arrays using two different methods. First, the gap widths were measured by BAE personnel using a vernier caliper. Second, the test arrays were sent to ARL where the same gaps were measured with a 7× optical loupe placed directly over the gaps. The tile arrays were then X-rayed in order to collect gap measurement data as it is normally taken from X-ray film.

In a target test coupon, the tile gaps are not accessible for direct measurement and must be measured from X-ray film. In this study, they were measured using two approaches. Initially, the gaps were measured from the films by using the same 7× loupe that was used for the direct visual measurements. Then, the gaps were measured in the normal manner, using scanned digital images of the film that were subsequently evaluated using AxioVision image measurement software (a product of Carl Zeiss, Inc.). The results from X-ray measurement methods were then compared with results of the direct measurement methods.

2. Experimental Procedures

2.1 Fabrication of the Ceramic Tile Arrays

The two arrays were made in duplicate process runs. Making duplicate arrays was done to get a rough sense of batch-to-batch variability. One surface of each of these arrays was intentionally kept exposed so that direct gap measurements could be made for use as baseline data. Each tile gap contained a spacer of cured graphite fiber/epoxy composite of average thickness 33 mils with a standard deviation of 3 mils. The graphite-tile arrays were packed tight using BAE's automated array packer, which is a step in their Build-to-Print (BtP) manufacturing process, developed under the U.S. Army Manufacturing Technology (ManTech) Program for ground vehicle armor production[1].

Next, two layers of Cytec FM94 epoxy film adhesive were placed over the array, followed by a cured polymer composite cover. The entire assembly was then cured by applying the appropriate 250 °F heat-pressure cycle.

2.2 Identification of Gaps

To organize the array for study, each gap of each tile array was numbered according to BAE's collected data. Gaps from test array BAE1 were numbered from 23 to 205, as shown in figure 1. Test array BAE2 was numbered from 1 to 205, as shown in figure 2. While performing the measurements, the diagrams in figures 1 and 2 were referenced in order to record and associate each measurement with the appropriate gap.

[1] *Low Cost Ceramic Armor-Automated Processing of Ceramic Armor Laminate*; ARL Cooperative Agreement No. W911NF-05-2-0002; BAE Systems U.S. Combat Systems-Pennsylvania.

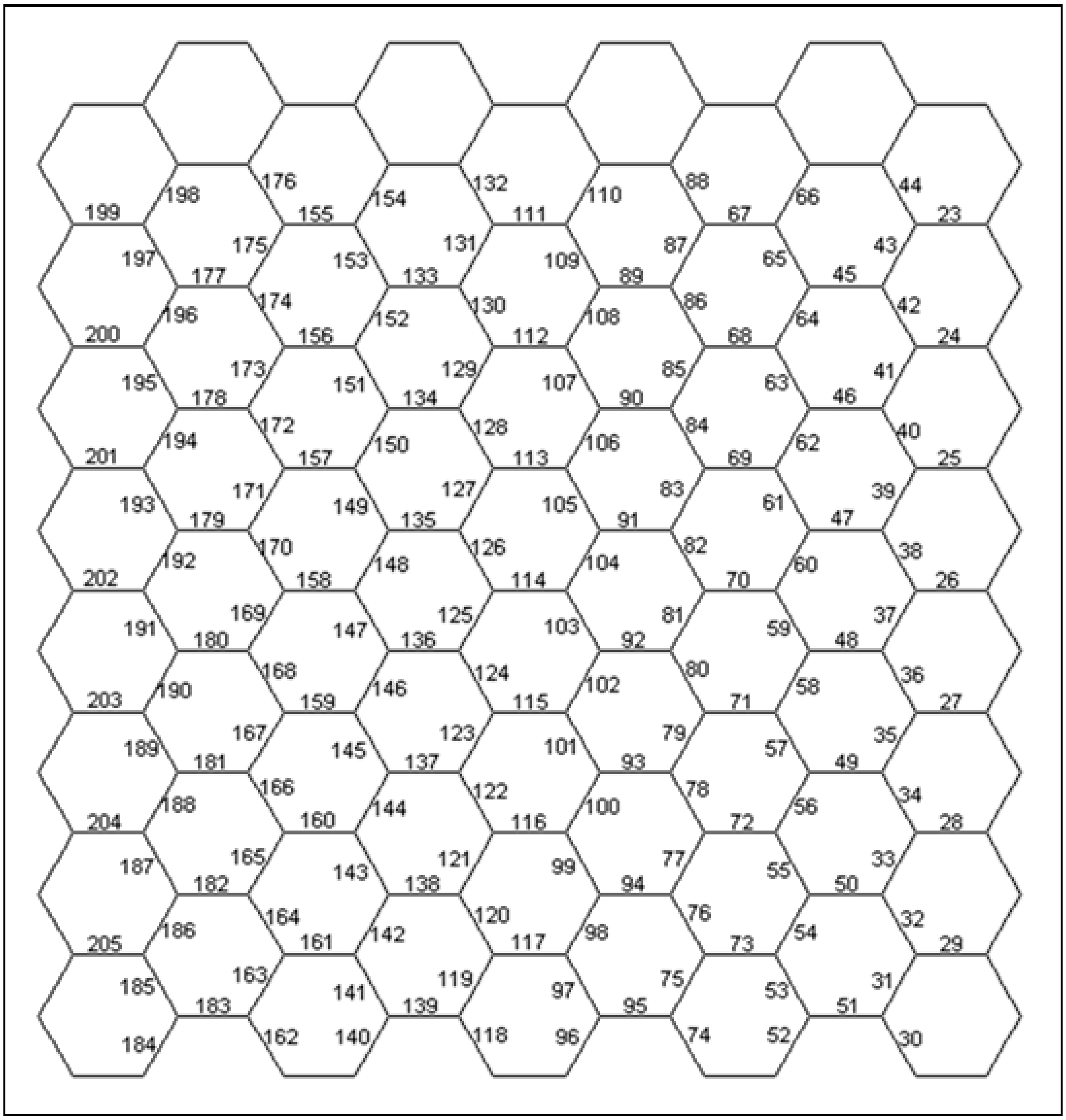

Figure 1. Diagram of BAE1 tile array with gap numbers.

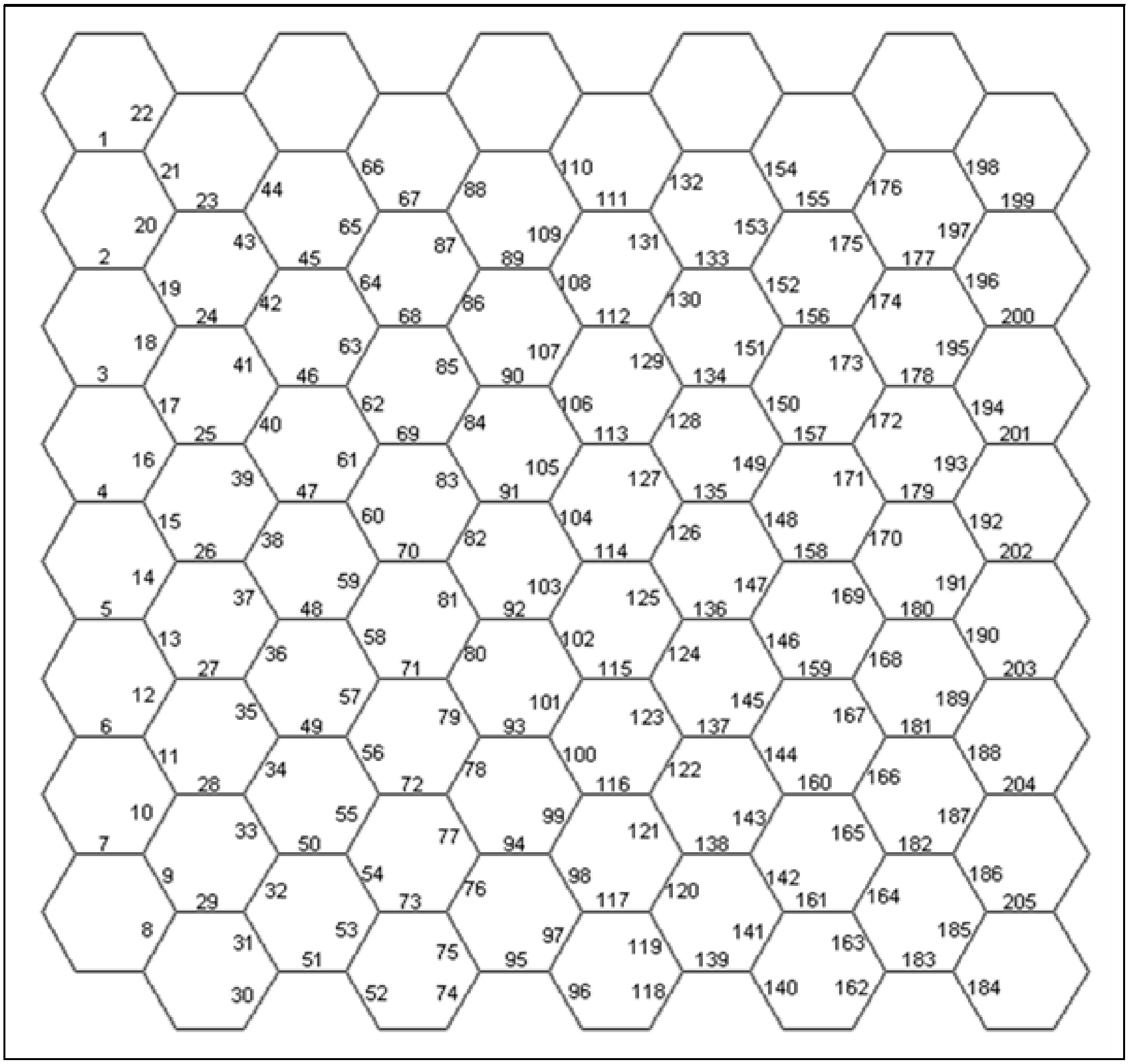

Figure 2. Diagram of BAE2 tile array with gap numbers.

2.3 BAE Vernier Caliper Method

All gaps were first measured at BAE-York using the vernier caliper method. The caliper was placed directly on top of each tile gap and the closest gauge thickness was recorded for the width of that gap. The accuracy of the caliper was 1.0 mil and the measurement was "eyeballed" under bright lighting to give a measurement resolution of approximately 2.0 mils. The nature of this eyeballed measurement method did not allow interpolation to get a finer resolution. This procedure was repeated for every gap on both test panels. The open side of test panels BAE1 and BAE2 are shown in figures 3 and 4.

2.4 ARL Optical Loupe Method

At ARL, a 7× optical loupe was used with bright lighting directly on the tile arrays to measure each gap. The loupe had a measurement grid marked every 5.0 mils. By interpolating between the grid lines, the resolution of the loupe measurement was approximately 2.5 mils. As with the vernier caliper method, this was repeated for each gap on each panel.

Figure 3. BAE1 tile array.

Figure 4. BAE2 tile array.

2.5 X-Ray Equipment and Imaging

Target test coupons at ARL are routinely sent to be X-rayed at the Aberdeen Test Center Industrial Radiography Facility, which is co-located with ARL at Aberdeen Proving Ground (APG), MD. This facility is well-equipped to maneuver and X-ray large, heavy armor test coupons. A diagram of the X-ray setup used for this study is shown in figure 5. The maximum beam voltage is 450 kV and the maximum current is 5 mA. The distance from the aperture to the tabletop is fixed at 80 in. The aperture opening can be varied from 2.5 mm to 5.5 mm.

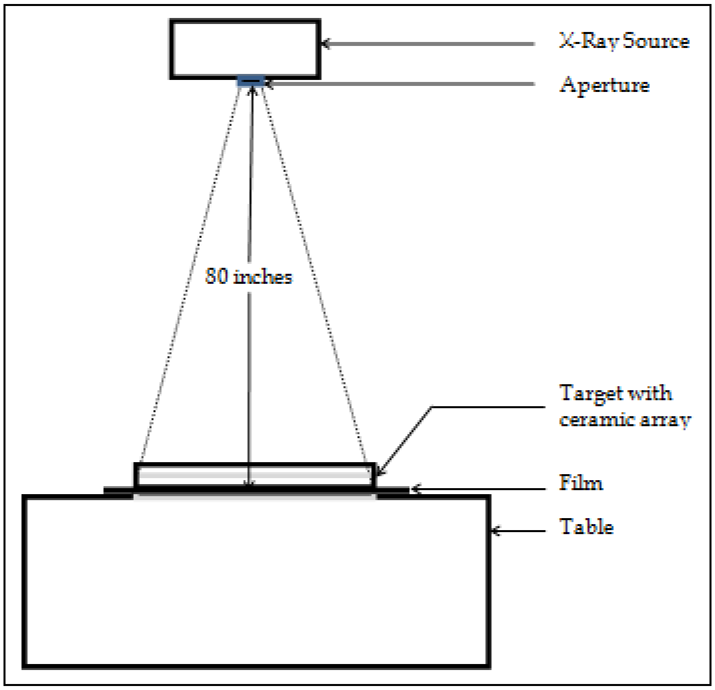

Figure 5. X-ray setup.

The X-ray film pack is placed directly on the tabletop and the array test coupon is placed directly on the film with the tile array side of the armor coupon facing away from the film. The film used was wet-developing Kodak 400AA. The film pack used lead image intensifiers that were 0.001-in thick and located immediately above and below the film.

For all the BAE1 and BAE2 X-rays taken, the voltage was set to 175 kV at maximum current (5 mA). The exposure time was 13 s with the aperture opening set at 5.5 mm. Each target was X-rayed by using six images of BAE1 and nine images for BAE2 (BAE2 was not trimmed to final size and had excess edge material, which made it bigger, requiring three more X-rays to complete its composite image). These film images were then digitally scanned and combined to form digital composite images of the entire tile arrays (figures 6 and 7).

2.6 Optical Loupe on X-ray Method

Wet film X-rays were taken of the BAE1 and BAE2 tile arrays using the equipment and setup described in section 2.5. To ensure coverage of every gap, multiple overlapping X-rays were taken of each array, as is routinely done when a target test coupon is X-rayed. Typically, many gaps are blurry on the film. These were excluded from the optical loupe data since meaningful measurements were not possible. Assembled X-ray images of BAE1 and BAE2 are shown in figures 6 and 7, respectively. A close-up of a sharp, measureable gap, as viewed through the optical loupe, is shown in figure 8. Figure 9 shows an example of a heavily blurred immeasurable gap.

To measure the gaps, the X-rays were affixed to an X-ray lightbox with bright backlighting and the 7× loupe was used to take the measurements to the nearest 2.5 mils.

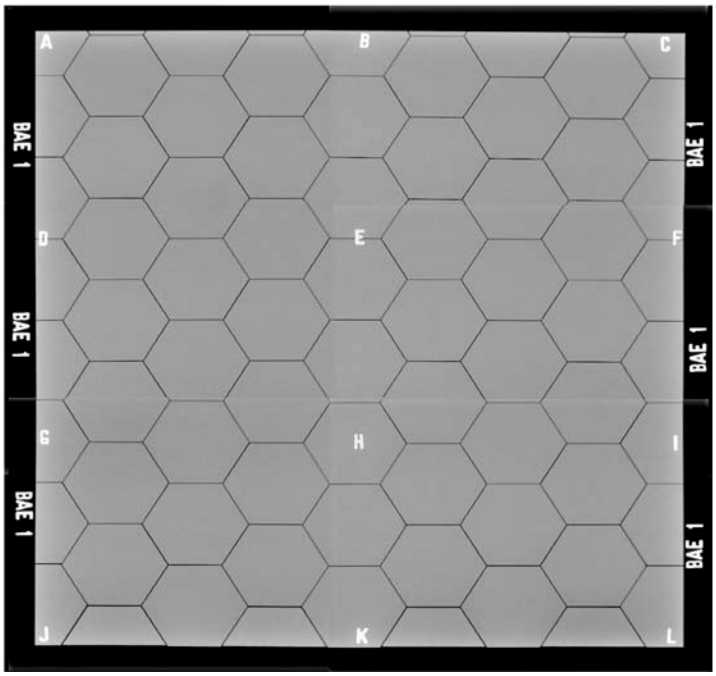

Figure 6. Composite of six X-rays to form a single complete picture of BAE1.

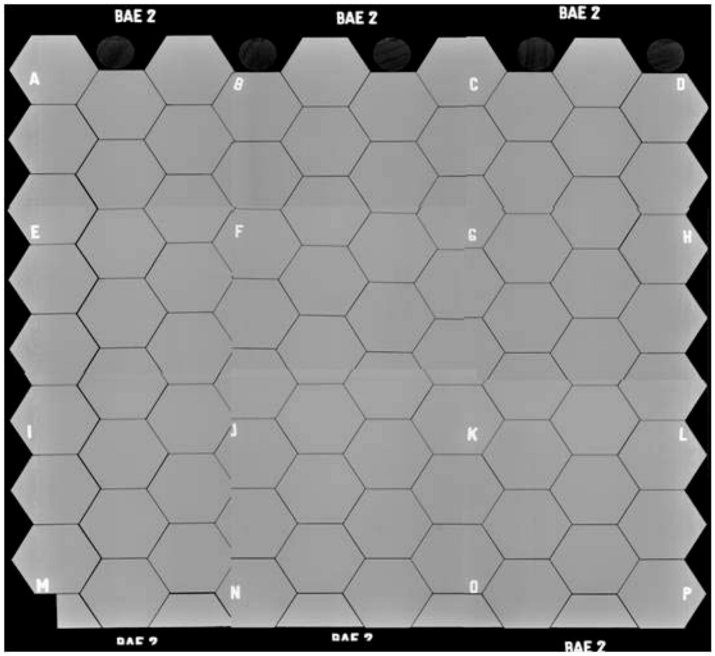

Figure 7. Composite of nine X-rays to form a single complete picture of BAE2.

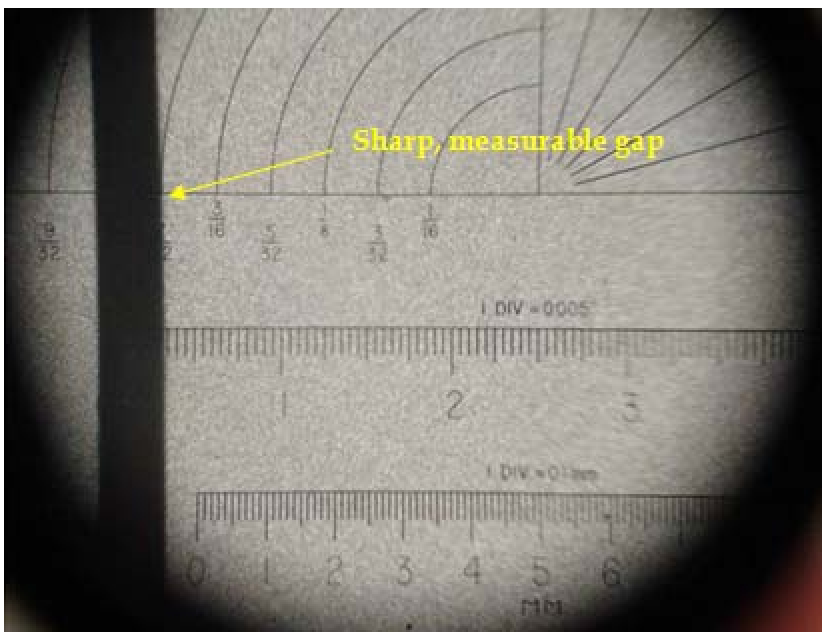

Figure 8. Close-up of a sharp, measureable gap looking through the 7× loupe.

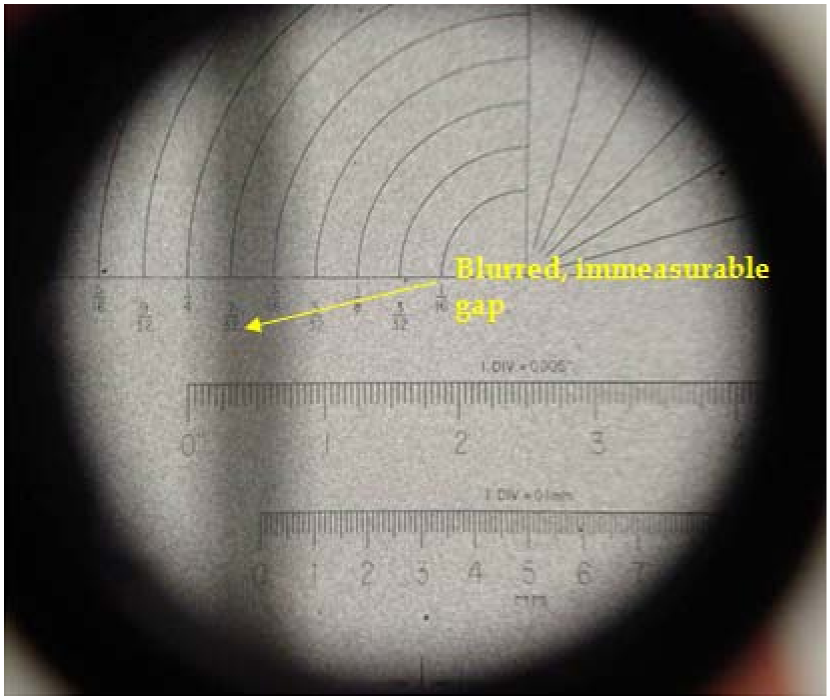

Figure 9. Close-up of a blurry, immeasurable gap looking through the 7× loupe.

2.7 AxioVision Measurement Software on Digitally Scanned X-ray Film Images

To measure the gaps using AxioVision, high resolution digitally scanned Digital Imaging and Communications in Medicine (DICOM) files of the X-rays were made. DICOM is an uncommon, very high resolution picture file format used in the medical field and the AxioVision software does not recognize these files. However, some of the DICOM picture resolution could be salvaged (about half) by using an intermediate image software translator called GNU Image Manipulation Program (GIMP). The GIMP software is capable of converting DICOM files into very large Tagged Image File Format (TIFF) files, which is a format that is compatible with AxioVision. The original DICOM files were 30.3 MB and 254 dpi. After GIMP translation and conversion to TIFF files, the final TIFF files used by AxioVision were 15.2 MB and 254 dpi.

These files were opened with AxioVision and, after setting the correct scaling, AxioVision's length-measuring function was used to measure the width of each gap. The measurement resolution of an image in AxioVision was 3.8 mils. This error arises from the fact that each square pixel had an edge length of 3.8 mils. A screenshot and close-up of a measurement done in AxioVision is shown in figures 10 and 11.

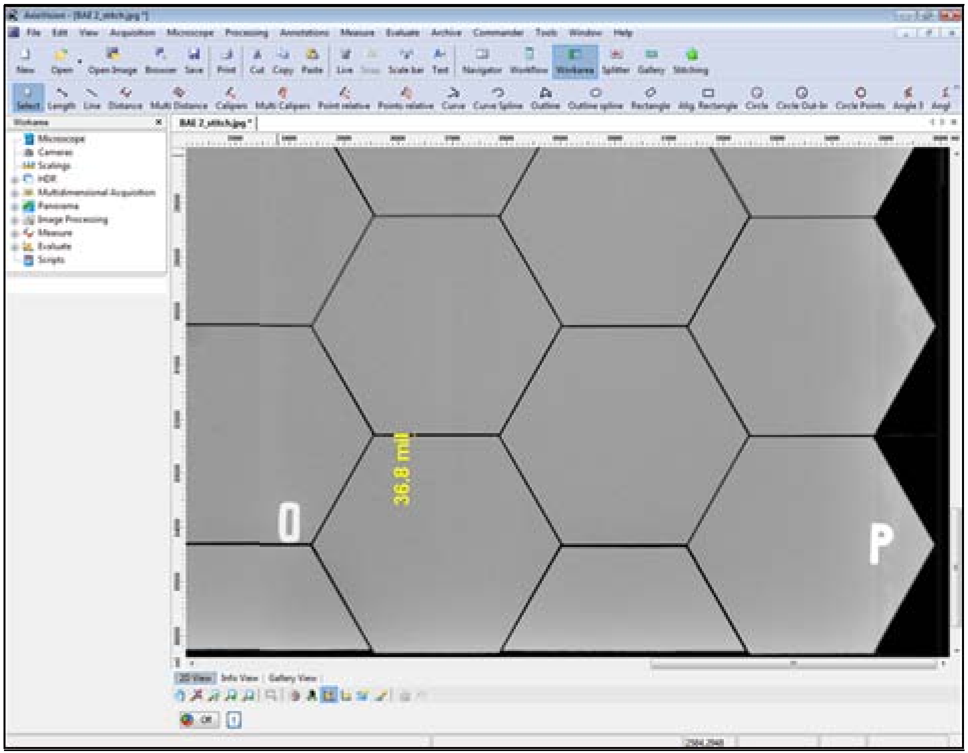

Figure 10. Screenshot of a gap measurement on X-ray film done in AxioVision.

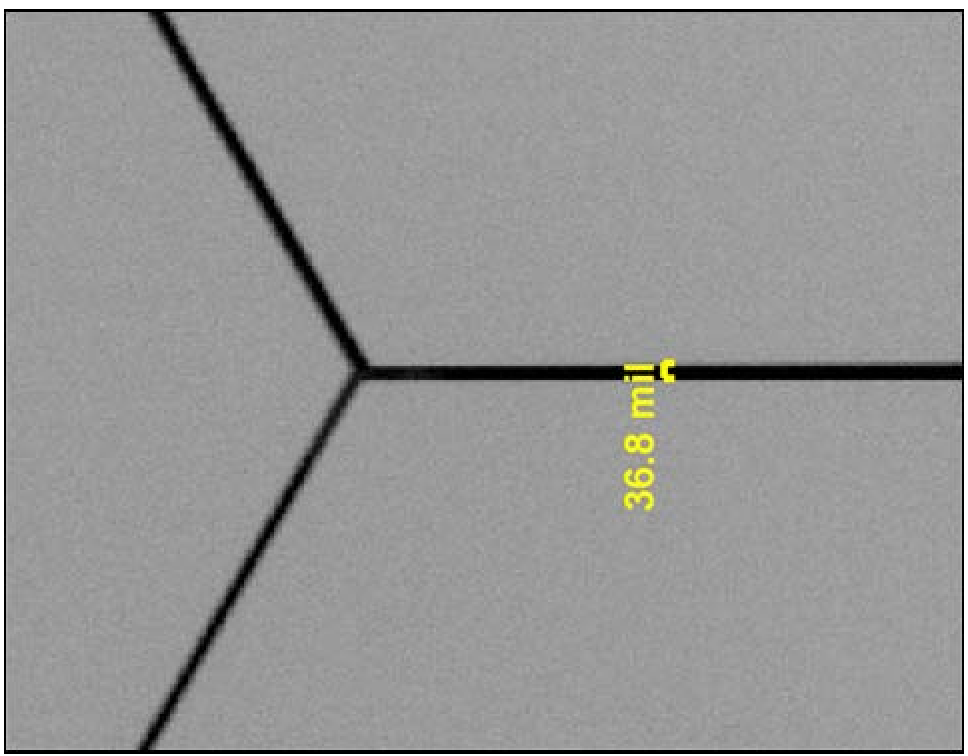

Figure 11. Zoomed screenshot of a gap measurement on X-ray film done in AxioVision.

3. Results and Discussion

3.1 BAE1 Gap Measurements

BAE1 results are summarized in figure 12 and table 1 (all measured raw data is compiled in the appendix). The gap size variation within the BAE1 tile array as determined by the four different measurement techniques is shown in figure 12. The direct optical measurement methods are represented by the red and blue curves. The red curve corresponds to the vernier caliper data while the blue curve represents the optical loupe data. The vertical axis corresponds to the frequency of a specific gap width value, while the horizontal axis corresponds to the range of gap widths. The bin width used was 5 mils.

The X-ray film methods show a wider range of variation in the gap width compared to the baseline direct visual measurement approaches. The indirect X-ray measurement methods are represented by the green and purple curves. The green curve indicates the results obtained using AxioVision software on the scanned X-ray film, while the purple curve corresponds to the optical loupe method applied to the X-ray film (where 29% of the gaps were measureable). Both of these methods can be used in actual practice to inspect and measure the array of a test target coupon, although the digitized AxioVision method is the one routinely used as it is a much more efficient process.

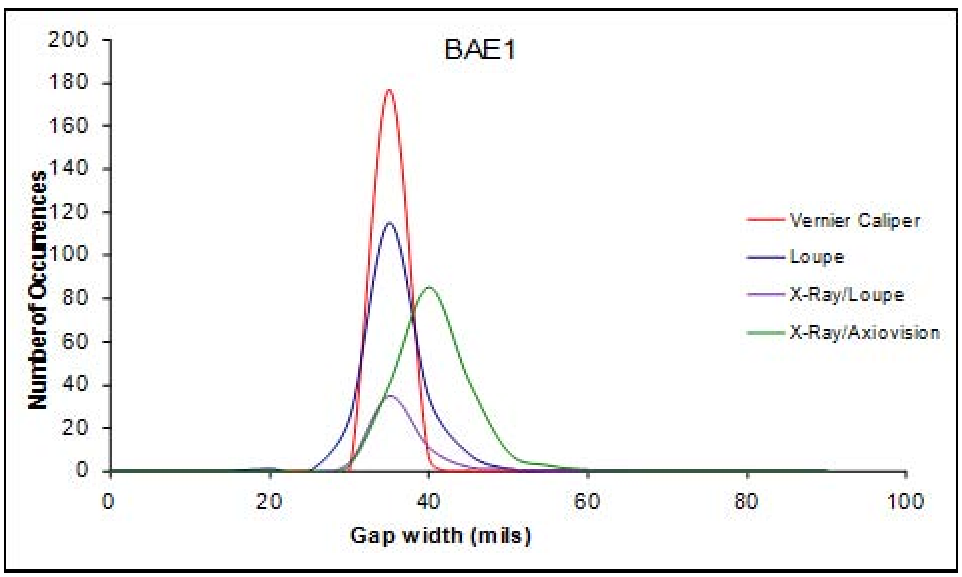

Figure 12. Graph of BAE1 results, showing the gap widths measured using the four different methods.

Table 1. Summary of BAE1 data for all four methods.

BAE1	Vernier Caliper on Array	7× Loupe-on-Array	7× Loupe on X-Ray Film[a]	AxioVision on X-Ray Images
Average gap size (mils)	33.6	34.8	35.4	38.8
Std. Dev. (mils)	0.83	3.73	3.71	4.52

[a]29% of gaps measured

3.2 BAE2 Gap Measurements

BAE2 results are summarized in figure 13 and table 2. 7% of the gaps were completely obscured by epoxy resin and were not measureable. In figure 13, the gap size variation within the BAE2 tile array is demonstrated by the same four measurement techniques. The direct measurement data are represented by the red and blue curves. The red curve corresponds to the vernier caliper data while the blue curve represents the loupe data. The vertical axis corresponds to the frequency of a specific gap width value, while the horizontal axis corresponds to the range of gap widths. The indirect measurement methods are represented by the green and purple curves. The green curve indicates the Axiovision on X-ray data while the purple curve corresponds to the loupe on X-ray data (where 53% of the gaps were measureable). Both of these methods show a wider range of variation in the gap width compared to direct approaches, as occurred in the BAE1 array.

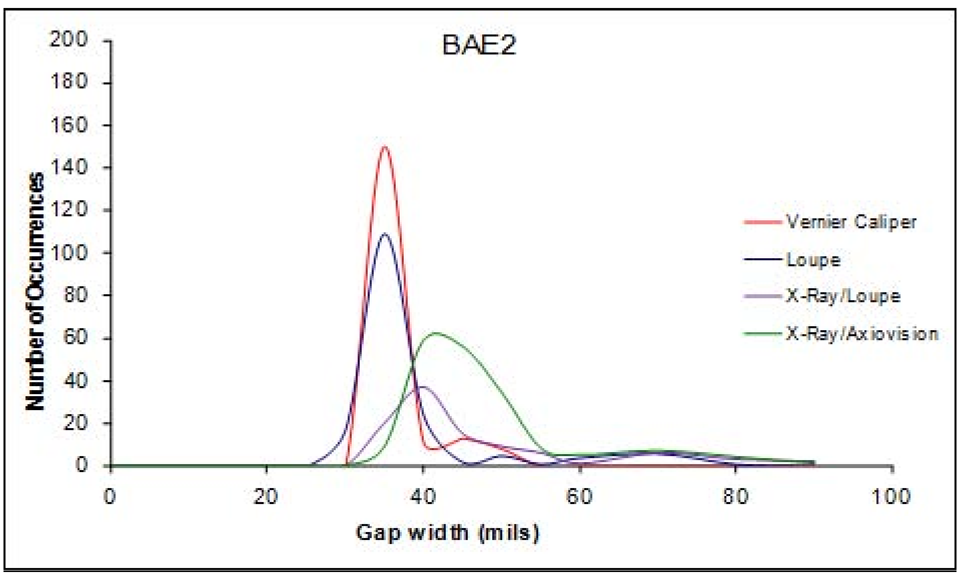

Figure 13. Graph of BAE2 results, showing the gap widths measured using the four different methods.

Table 2. Summary of BAE2 data for all four methods.

BAE2	Vernier caliper on Array	7× Loupe-on-Array[a]	7× Loupe on X-Ray Film[b]	AxioVision on X-Ray Images
Average gap size (mils)	35.5	37.7	44.6	45.0
Std. Dev. (mils)	4.26	8.51	11.27	8.63

[a] 93% of gaps measured

[b] 53% of gaps measured

3.3 X-ray Measurement Methods Comparison

Both X-ray methods produce data that give a useful qualitative and quantitative portrayal of the tile array gaps. The direct measurement baseline methods are more accurate than the indirect X-ray methods and are the basis for evaluating the X-ray film methods, which are the methods that must be used when assessing an actual target coupon array. Use of a vernier caliper worked well as a baseline for determining the gap widths and was in excellent agreement with the direct optical loupe, as is seen in figures 12 and 13. However, since this method does not interpolate well and relied on eyeballing, it introduced an element of parallax error and, while it generated data that matched up well with the direct optical loupe baseline, the values recorded are somewhat biased toward discrete uniformity. Therefore, the more accurate baseline method used in this study for gap measurements was the direct method using the optical loupe. Due to the clear visibility of the measurement grid and the ability to objectively interpolate between the grid markings, this method gives a truer measurement. (A 7× magnification loupe was chosen for this study. It is noted that higher magnification loupes with more refined grids can be used with equal ease and would return even more accurate data with the same ability to interpolate.) For this reason, the direct optical loupe values were used as the preferred baseline for comparison.

By comparing results from direct and X-ray measurement methods, it is concluded that the average of the tile gap sizes can be estimated through X-ray methods; however, the level of accuracy for X-ray methods is open to discussion. In particular, gap distribution curves for X-ray measurements result in positive shifts. This indicates that X-ray measurements skew the gap widths upward and overestimate them. Identifying and extracting a corrective scaling factor might be possible if enough data is gathered. If this is the case, the factor could be determined by further study and applied to the X-ray measurements to correct this systematic error and accordingly, the level of accuracy could be improved.

The gap measurement and variability remain essentially unchanged when the measurement method is changed from a loupe measurement off the X-ray film or is digitally scanned and measured on a computer monitor using the AxioVision software. This is important, as the digital method is a much more efficient means of acquiring this data. It also has the potential for measurement automation in the future. If good quality image scanning and measurement software is used, it is not necessary to measure gaps directly off the film to get equivalent results. The use of AxioVision (or other measurement software) as a measurement tool results in data that is as good as a direct reading off the film with a loupe. In addition, digitization of the image

for measurement by the software results in a much higher number of readable gaps, significantly increasing the statistical confidence in the data.

The AxioVision software did a much better job of interpreting blur than was able to be done using the loupe and human eye alone. This is because the software could magnify the digital image down to the pixel level and discriminate gray levels much better than the human eye. For this reason, the software was able to get a consistent, objective measurement from every gap, compared to 29% of the gaps when the loupe was used directly on the film on BAE1 and 53% on BAE2. However, when dealing with blur, AxioVision is more consistent, but not necessarily more accurate.

3.4 Production Batch Comparison

Comparing the two data sets by batch, which is shown in table 3, gives some insight into the repeatability of the process itself, albeit from a very small sampling of only two process runs. The data clearly shows that the gap widths in the BAE1 array were both smaller and less variable than those of BAE2. This was true across all measurement methods: the vernier caliper method recorded an average width increase of 1.9 mils (5.6%), the loupe-on-array method recorded an average increase of 2.9 mils (8.3%), the loupe-on-film method recorded an average increase of 9.2 mils (26.0%), and the AxioVision digital measurement method recorded an average increase of 6.2 mils (16.0%). The manufactured array quality of BAE1 is clearly better than that of BAE2 even though the runs were duplicates. This does not mean that the BAE2 run was out of specification—it simply means it was different enough to be detected by these measurement methods. Looking at the loupe distribution curve in figure 13, it clearly shows two small outlier peaks near 50 mils and 70 mils. At this time, there are no production limits set to determine an acceptable range of gap widths. The batch data is valuable as it provides a snapshot of batch-to-batch variability of the array packing portion of the current BtP process.

Note that the direct measurement methods show the two runs as much more repeatable than the two X-ray methods, which both indicated much larger gaps width increases. These direct visual methods are much more accurate and were created to give a baseline for X-ray evaluation for this study. So these are the values that depict the variability between the BAE1 and BAE2 production runs; the X-ray data should not be, and is not, used for this purpose.

Table 3. Comparison of array process batches BAE1 and BAE2.

BAE1 and BAE2 Comparison	Vernier Caliper on Array		7× Loupe-on-Array		7× Loupe on X-Ray Film		AxioVision on X-ray Images	
	BAE1	**BAE2**	**BAE1**	**BAE2**	**BAE1**	**BAE2**	**BAE1**	**BAE2**
Average gap size (mils)	33.6	35.5	34.8	37.7	35.4	44.6	38.8	45.0
Std. Dev. (mils)	0.83	4.26	3.73	8.51	3.71	11.27	4.52	8.63

3.5 Goal Versus Actual Gap Widths

This study afforded the opportunity to portray what can be expected when manufacturing ceramic armor arrays by a process such as the current BtP method. Essentially, this process packs the array tightly, then applies a compressive load around the perimeter to hold the array in place until bonding is complete, at which time the compressive frame is released. The goal would be for every gap to be 33 mils with a variability of zero. This, of course, is not realistic. The nature of the process does not allow the gaps to be less than the spacer width (in this study 33 mils, on average), but certainly allows them to be larger. The two data sets in this study represent a first hard look at realistic deviations from the idealized case. This is a vitally important metric of ceramic armor as ballistic performance is very sensitive to gap widths.

Using the direct loupe data set as the true values of gap widths, it is seen that the actual average gap width of the BAE1 array was 1.8 mils above the goal, with a standard deviation of 3.7 mils. Moreover, it is important to consider the maximum gap (47.5 mils), as this represents the location of greatest ballistic vulnerability. So, all gaps on the array fall at or below 14.5 mils above the goal.

BAE2 was made in a separate processing run and represents the repeatability of the process. It processed to an actual average gap width which was 4.7 mils above the goal, with a standard deviation of 8.5 mils. Its maximum gap was 75.0 mils. All gaps in this array fall between 0.0 and 42.0 mils above the goal. This is quite a difference between batches and underscores a need for non-destructive quality control measurements and setting acceptable limits to deviations from gap width goals.

4. Conclusions

The direct optical measurement methods used in this study served as an excellent means to measure actual gap widths and provided a baseline for comparison by which to evaluate the X-ray measurements. In practice, direct measurement of gaps is not possible. X-ray measurement is the only non-destructive evaluation (NDE) method available to give quantifiable values for gap widths, which are critical to ballistic performance of the ceramic tile array. This study shows that the X-ray methods give a good portrayal of array quality, but measurement accuracy can be improved. It was revealed that the X-ray method skews the gap width measurements higher, and that this skewing was not consistent (it varied on the order of 2 to 20% in this study). Since ballistic performance is sensitive to gap widths, it is important to have an accurate and reliable NDE quality control method that can be counted on to obtain correct values. It is strongly recommended that a new X-ray system, designed specifically for the accurate measure of tile gaps, be put in place.

A common issue with X-ray films is that there is often inconsistency in terms of sharpness across the overall area of an X-ray image. The X-ray images produced for this study demonstrate this problem. It is of interest to find a way to reduce or eliminate the number of blurred gaps while increasing the measurement accuracy on the X-ray images. Optical distortions are at work here that can be greatly reduced. Improvement in the resolution of the X-ray process and the film itself is what is needed to make X-ray measurement more accurate and less blurred. As noted above, appropriate equipment design is a key to improvement. A digital radiography system would appear to be the path forward.

This study has demonstrated that the current digital X-ray measurement method in use is just as accurate as a loupe measurement taken directly off the film. The resolution of the scanned images can be no better than the film they were scanned from. It has been shown that the subsequent digital measurement by AxioVision software does not degrade the measurement and even increases repeatability somewhat over the manual loupe method.

Appendix. Measured Gap Data

Table A-1. Data collected from BAE1.

Location ID	Vernier Caliper on Array (mils)	7× Loupe-on-Array (mils)	7× Loupe on X-ray Film (mils)*	AxioVision on X-ray Images (mils)
23	34.0	32.5		35
24	34.0	32.5	35.0	33
25	35.0	35.0		34
26	34.0	35.0		30
27	33.0	20.0	32.5	31
28	34.0	42.5		41
29	34.0	27.5	40.0	30
30	34.0	47.5		54
31	33.0	35.0		41
32	33.0	40.0		39
33	33.0	35.0		36
34	33.0	40.0		39
35	36.0	40.0		38
36	34.0	40.0		43
37	36.0	35.0		37
38	34.0	35.0		40
39	33.0	35.0		35
40	34.0	35.0		40
41	33.0	37.5		43
42	34.0	37.5		43
43	36.0	35.0		40
44	34.0	40.0		43
45	35.0	32.5		41
46	34.0	32.5		36
47	34.0	35.0		38
48	34.0	35.0	35.0	35
49	34.0	30.0		40
50	37.0	40.0		47
51	36.0	45.0		52
52	35.0	30.0		36
53	33.0	40.0		42
54	33.0	35.0		41
55	35.0	35.0		38
56	34.0	35.0	35.0	38

* Blank entries represent immeasurable data points

Table A-1. Data collected from BAE1 (continued).

Location ID	Vernier Caliper on Array (mils)	7× Loupe-on-Array (mils)	7× Loupe on X-ray Film (mils)*	AxioVision on X-ray Images (mils)
57	34.0	35.0		40
58	34.0	34.0		35
59	35.0	33.5		38
60	34.0	33.5	32.5	36
61	34.0	30.0	35.0	39
62	33.0	30.0		39
63	34.0	40.0		37
64	34.0	32.5		35
65	35.0	30.0		44
66	33.0	35.0	35.0	38
67	33.0	35.0		49
68	34.0	34.5	35.0	37
69	33.0	35.0		39
70	34.0	30.0		37
71	34.0	32.5		36
72	34.0	37.0		42
73	35.0	40.0	40.0	42
74	33.0	37.0		42
75	33.0	35.0	35.0	38
76	34.0	37.5	35.0	42
77	33.0	35.0		41
78	33.0	35.0		37
79	34.0	35.0	35.0	40
80	34.0	35.0	32.5	37
81	32.0	35.0	30.0	38
82	33.0	35.0		34
83	32.0	30.0		35
84	34.0	35.0		42
85	33.0	35.0	35.0	40
86	34.0	32.5	32.5	39
87	34.0	35.0		43
88	33.0	35.0		37
89	33.0	32.5		42
90	33.0	35.0	35.0	38
91	33.0	32.5		38
92	33.0	32.5	32.5	36
93	33.0	35.0		43
94	34.0	40.0		42
95	33.0	45.0		52

* Blank entries represent immeasurable data points

Table A-1. Data collected from BAE1 (continued).

Location ID	Vernier Caliper on Array (mils)	7× Loupe-on-Array (mils)	7× Loupe on X-ray Film (mils)*	AxioVision on X-ray Images (mils)
96	34.0	30.0		43
97	33.0	35.0		43
98	33.0	40.0		42
99	33.0	32.5		39
100	33.0	35.0		41
101	33.0	35.0	35.0	38
102	33.0	32.5		38
103	33.0	35.0		35
104	33.0	30.0		37
105	35.0	32.5	35.0	47
106	33.0	35.0		48
107	34.0	40.0		44
108	34.0	40.0		43
109	35.0	35.0	30.0	42
110	34.0	35.0		42
111	33.0	30.0		36
112	34.0	32.5	35.0	37
113	34.0	32.5		31
114	34.0	32.5		35
115	33.0	32.5	32.5	34
116	33.0	35.0		40
117	34.0	37.5	37.5	39
118	33.0	35.0		42
119	33.0	35.0		40
120	32.0	32.5		40
121	33.0	32.5		35
122	33.0	32.5		40
123	33.0	35.0		35
124	34.0	40.0		39
125	34.0	35.0		37
126	34.0	40.0		36
127	34.0	42.5		38
128	34.0	32.5		34
129	34.0	35.0		37
130	33.0	32.5		36
131	33.0	35.0		35
132	33.0	32.5		35
133	33.0	35.0		36
134	33.0	37.5	37.5	37
135	33.0	30.0		38
136	33.0	32.5		36

* Blank entries represent immeasurable data points

Table A-1. Data collected from BAE1 (continued).

Location ID	Vernier Caliper on Array (mils)	7× Loupe-on-Array (mils)	7× Loupe on X-ray Film (mils)*	AxioVision on X-ray Images (mils)
137	33.0	35.0		36
138	33.0	40.0		44
139	33.0	30.0	50.0	58
140	33.0	30.0		42
141	34.0	37.5		35
142	33.0	35.0		35
143	33.0	35.0		37
144	33.0	32.5	35.0	39
145	34.0	32.5		34
146	32.0	30.0		34
147	34.0	32.5		34
148	33.0	32.5	35.0	34
149	33.0	32.5	35.0	37
150	33.0	35.0		37
151	33.0	35.0		33
152	33.0	30.0	35.0	32
153	34.0	35.0		36
154	35.0	32.5	30.0	35
155	35.0	35.0		41
156	35.0	30.0	32.5	36
157	33.0	35.0		40
158	33.0	30.0		36
159	34.0	32.5	32.5	37
160	34.0	35.0		38
161	33.0	35.0	40.0	42
162	34.0	30.0	40.0	34
163	34.0	30.0	37.5	40
164	33.0	35.0	42.5	44
165	33.0	32.5		41
166	33.0	32.5		44
167	33.0	35.0	35.0	36
168	33.0	35.0	37.5	40
169	33.0	35.0		38
170	33.0	35.0	32.5	33
171	34.0	35.0	37.5	34
172	34.0	30.0		35
173	35.0	32.5	30.0	37
174	35.0	40.0	35.0	39
175	35.0	35.0		40
176	34.0	37.5		34
177	33.0	35.0		36

* Blank entries represent immeasurable data points

Table A-1. Data collected from BAE1 (continued).

Location ID	**Vernier Caliper on Array (mils)**	**7× Loupe-on-Array (mils)**	**7× Loupe on X-ray Film (mils)***	**AxioVision on X-ray Images (mils)**
178	33.0	32.5	32.5	38
179	33.0	32.5		38
180	33.0	40.0		35
181	33.0	32.5		42
182	35.0	30.0		44
183	33.0	35.0	45.0	42
184	34.0	45.0		50
185	33.0	45.0		43
186	33.0	35.0		50
187	33.0	37.5		44
188	34.0	37.5		48
189	36.0	37.5	35.0	49
190	33.0	42.5		46
191	33.0	40.0		40
192	33.0	37.5		38
193	33.0	35.0	35.0	41
194	34.0	32.5		37
195	34.0	35.0		38
196	34.0	37.5		40
197	33.0	35.0		32
198	33.0	45.0		38
199	33.0	35.0		34
200	34.0	32.5	32.5	35
201	33.0	27.5	37.5	30
202	34.0	30.0		34
203	33.0	32.5	32.5	35
204	35.0	32.5	32.5	33
205	34.0	37.5	40.0	38
AVG	33.6	34.8	35.4	38.8
STD	0.83	3.73	3.71	4.52

* Blank entries represent immeasurable data points

Table A-2. Data collected from BAE2.

Location ID	Vernier Caliper on Array (mils)	7× Loupe-on-Array (mils)*	7× Loupe on X-ray Film (mils)*	AxioVision on X-ray Images (mils)
1	33.0	37.5		39
2	31.0	35.0	37.5	37
3	32.0	35.0		40
4	33.0	37.5		43
5	33.0	40.0	42.5	38
6	33.0	40.0		48
7	32.0	37.5		42
8	33.0		62.5	57
9	42.0	67.5	70.0	65
10	45.0	60.0	65.0	62
11	48.0	67.5	72.5	71
12	48.0	60.0		65
13	49.0	62.5		71
14	47.0	60.0	67.5	64
15	49.0	60.0	65.0	63
16	43.0	70.0		67
17	45.0	65.0	72.5	76
18	44.0	70.0	75.0	69
19	48.0	75.0	85.0	79
20	49.0	55.0	62.5	58
21	46.0	50.0	55.0	51
22	41.0	37.5		44
23	33.0	37.5	40.0	38
24	32.0	30.0	45.0	37
25	32.0	32.5		41
26	32.0	30.0	32.5	36
27	34.0	35.0		41
28	34.0	35.0		44
29	34.0		37.5	39
30	33.0			48
31	33.0		40.0	39
32	33.0	40.0	50.0	47
33	34.0	32.5		46
34	34.0	50.0	50.0	49
35	34.0	40.0	40.0	38
36	33.0	47.5		54
37	45.0	40.0	42.5	45
38	35.0	45.0	52.5	50
39	36.0	42.5		46
40	34.0	50.0		48

* Blank entries represent immeasurable data points

Table A-2. Data collected from BAE2 (continued).

Location ID	Vernier Caliper on Array (mils)*	7× Loupe-on-Array (mils)*	7× Loupe on X-ray Film (mils)*	AxioVision on X-ray Images (mils)
41	33.0	40.0	45.0	42
42	34.0	37.5	47.5	43
43	33.0	37.5	45.0	42
44	34.0	35.0	35.0	34
45	34.0	32.5	37.5	37
46	34.0	40.0		44
47	37.0	32.5	40.0	41
48	33.0	35.0	40.0	40
49	35.0	35.0		46
50	32.0	32.5	40.0	46
51	32.0		87.5	39
52	33.0			88
53	33.0	35.0		51
54	33.0	32.5		50
55	33.0	35.0		49
56		30.0		38
57	34.0	35.0	47.5	51
58	34.0	35.0		47
59	41.0	40.0		55
60	32.0	30.0		50
61	33.0	35.0		42
62	34.0	35.0		40
63	32.0	37.5	45.0	41
64	34.0	35.0		43
65	33.0	35.0		45
66	34.0	35.0		44
67	35.0	37.5	47.5	42
68	34.0	30.0	45.0	36
69	33.0	32.5		41
70	34.0	35.0	37.5	35
71	33.0	35.0		45
72	40.0	35.0		45
73	44.0	47.5	50.0	52
74	45.0		45.0	40
75	36.0	40.0	55.0	50
76	33.0	35.0	50.0	43
77	33.0	32.5	35.0	34
78	35.0	35.0		40
79	34.0	35.0	42.5	44
80	35.0	35.0	35.0	37
81	34.0	35.0	40.0	40

* Blank entries represent immeasurable data points

Table A-2. Data collected from BAE2 (continued).

Location ID	Vernier Caliper on Array (mils)	7× Loupe-on-Array (mils)*	7× Loupe on X-ray Film (mils)*	AxioVision on X-ray Images (mils)
82	34.0	35.0	47.5	43
83	33.0	30.0	35.0	34
84	34.0	32.5	37.5	37
85	36.0	35.0	52.5	42
86	34.0	35.0	40.0	40
87	35.0	32.5	37.5	39
88	33.0	32.5		46
89	34.0	32.5	35.0	37
90	34.0	35.0		44
91	34.0	35.0		43
92	34.0	32.5	40.0	40
93	35.0	35.0		44
94	44.0	35.0	45.0	46
95	35.0		55.0	57
96	35.0		50.0	43
97	34.0	35.0	42.5	40
98	34.0	40.0	42.5	45
99	33.0	35.0	37.5	36
100	33.0	35.0		38
101	33.0	30.0	45.0	39
102	34.0	30.0	35.0	35
103	34.0	35.0	32.5	38
104	35.0	30.0		39
105	33.0	35.0	37.5	36
106	35.0	35.0	40.0	36
107	33.0	35.0	45.0	41
108	35.0	30.0	37.5	37
109	35.0	35.0	35.0	37
110	35.0	32.5		45
111	33.0	35.0		44
112	36.0	35.0		41
113	34.0	35.0		47
114	33.0	32.5	35.0	35
115	36.0	32.5		45
116	33.0	32.5		47
117	34.0	37.5		38
118	35.0			52
119	33.0	32.5		47
120	33.0	35.0		48
121	35.0	30.0		47
122	33.0	35.0	37.5	39

* Blank entries represent immeasurable data points

Table A-2. Data collected from BAE2 (continued).

Location ID	Vernier Caliper on Array (mils)	7× Loupe-on-Array (mils)*	7× Loupe on X-ray Film (mils)*	AxioVision on X-ray Images (mils)
123	34.0	30.0	37.5	40
124	35.0	32.5		47
125	35.0	30.0		46
126	34.0	35.0		47
127	34.0	35.0		38
128	34.0	32.5	40.0	39
129	34.0	32.5		45
130	33.0	35.0		49
131	33.0	35.0		52
132	35.0	35.0	40.0	46
133	35.0	35.0	32.5	38
134	34.0	35.0		44
135	33.0	32.5	40.0	44
136	34.0	32.5	35.0	39
137	44.0	32.5		41
138	34.0	37.5	45.0	44
139	34.0		55.0	58
140	33.0			44
141	43.0	35.0		48
142	33.0	35.0		46
143	37.0	32.5		39
144	34.0	35.0	40.0	45
145	34.0	35.0	35.0	35
146	34.0	35.0		48
147	34.0	30.0		42
148	34.0	35.0	40.0	42
149	34.0	35.0		48
150	34.0	35.0	37.5	38
151	33.0	35.0	35.0	49
152	34.0	35.0		45
153	33.0	35.0		45
154	33.0	35.0	35.0	36
155	33.0	35.0		43
156	33.0	30.0	40.0	39
157	35.0	32.5		48
158	34.0	30.0	37.5	39
159	36.0	35.0		42
160	35.0	32.5		46
161	33.0	37.5	40.0	42
162	35.0		40.0	41
163	34.0	30.0	32.5	35

*Blank entries represent immeasurable data points

Table A-2. Data collected from BAE2 (continued).

Location ID	Vernier Caliper on Array (mils)	7× Loupe-on-Array (mils) *	7× Loupe on X-ray Film (mils)*	AxioVision on X-ray Images (mils)
164	33.0	40.0	37.5	38
165	35.0	32.5	37.5	40
166	33.0	35.0		42
167	34.0	35.0		39
168	34.0	35.0		40
169	33.0	35.0	35.0	36
170	33.0	35.0	35.0	35
171	34.0	35.0		44
172	36.0	35.0		42
173	34.0	35.0	40.0	38
174	35.0	35.0	32.5	36
175	34.0	35.0	40.0	40
176	34.0	35.0	37.5	38
177	37.0	35.0	37.5	39
178	34.0	32.5		44
179	34.0	32.5		43
180	33.0	32.5	32.5	40
181	34.0	35.0		40
182	33.0	40.0		45
183	33.0		57.5	60
184	33.0		52.5	52
185	33.0	32.5		46
186	34.0	45.0		52
187	33.0	42.5	42.5	44
188	33.0	47.5	50.0	46
189	35.0	45.0	47.5	55
190	34.0	47.5		56
191	34.0	45.0		56
192	33.0	37.5		51
193	34.0	35.0	40.0	41
194	34.0	57.5	62.5	59
195	34.0	55.0	55.0	53
196	34.0	50.0		58
197	33.0	40.0		51
198	38.0	52.5		65
199	42.0	40.0		44
200	40.0	35.0		39
201	45.0	35.0		45
202	48.0	30.0	37.5	38
203	48.0	35.0		40

* Blank entries represent immeasurable data points

Table A-2. Data collected from BAE2 (continued).

Location ID	Vernier Caliper on Array (mils)	7× Loupe-on-Array (mils)	7× Loupe on X-ray Film (mils)*	AxioVision on X-ray Images (mils)
204	49.0	32.5		43
205	50.0	37.5	40.0	40
AVG	35.5	37.7	44.6	45.0
STD	4.3	8.51	11.27	8.63

* Blank entries represent immeasurable data points

INTENTIONALLY LEFT BLANK.

List of Symbols, Abbreviations, and Acronyms

APG	Aberdeen Proving Ground
ARL	U.S. Army Research Laboratory
BAE	BAE Systems U.S. Combat Systems-Pennsylvania, York, PA
BtP	Build-to-Print
DICOM	Digital Imaging and Communications in Medicine
GIMP	GNU Image Manipulation Program
ManTech	U.S. Army Manufacturing Technology Program
NDE	non-destructive evaluation
TIFF	Tagged Image File Format

NO. OF COPIES	ORGANIZATION
1 (PDF only)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FORT BELVOIR VA 22060-6218
1	DIRECTOR US ARMY RESEARCH LAB IMNE ALC HRR 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB RDRL CIM L 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB RDRL CIM P 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB RDRL D 2800 POWDER MILL RD ADELPHI MD 20783-1197
	ABERDEEN PROVING GROUND
1	DIR USARL RDRL CIM G (BLDG 4600)

NO. OF COPIES	ORGANIZATION
1	RDECOM TARDEC COMBAT VEHICLE ARMOR DEVELOPMENT ATO–GROUND SYSTEM SURVIVABILITY ATTN RDTA RS/MS 263 S KLANN 6501 E 11 MILE RD WARREN MI 48397-5000
1	RDECOM TARDEC BLDG 200D ATTN RDTA RS/MS 255 V GENDLIN 6501 E. 11 MILE RD WARREN MI 48397-5000
2	BAE SYSTEMS–YORK ATTN R SCIORTINO ATTN W FALLON BLDG 20 COMPOSITES LAB 1100 BAIRS RD YORK PA 17408
1	BAE SYSTEMS–SANTA CLARA ATTN D SCHADE PO BOX 359 SANTA CLARA CA 95050
1	GENERAL DYNAMICS LAND SYSTEMS ATTN G TEAL P.O. BOX 1800 WARREN MI 48090-1800
1	GENERAL DYNAMICS LAND SYSTEMS ATTN K TRAN M/Z 435 01 24 6000 E 17 MILE RD STERLING HEIGHTS MI 48313
	ABERDEEN PROVING GROUND
56	RDRL LOA F M ADAMSON RDRL WM J SMITH RDRL WMM J ZABINSKI R DOWDING J BEATTY RDRL WMM A M MAHER S GHIORSE (6 CPS) J WOLBERT L HOLMES H MAUPIN RDRL WMM B M VANLANDINGHAM B CHEESEMAN C YEN T BOGETTI RDRL WMM C J LA SCALA R JENSEN J ROBINETTE RDRL WMM D E CHIN W GREEN R BRENNAN RDRL WMM E M PEPI T JESSEN J CAMPBELL M BRATCHER J SANDS RDRL WMM F R CARTER K DOHERTY RDRL WMM G A RAWLETT RDRL WMP P BAKER S SCHOENFELD RDRL WMP A B RINGERS RDRL WMP B C HOPPEL RDRL WMP C T BJERKE RDRL WMP D J RUNYEON B SCOTT V HERNANDEZ S HUG M KEELE D PETTY RDRL WMP E S BARTUS M BURKINS D GALLARDY W GOOCH D HACKBARTH E HORWATH M KLUSEWITZ C KRAUTHAUSER M LOVE RDRL WMP F N GNIAZDOWSKI RDRL WMP G N ELDREDGE RDRL WML M ZOLTOSKI

INTENTIONALLY LEFT BLANK.